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Yield stability of soybean mixtures

by

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INTRODUCTION

One important factor in efficient soybean [Glycine max (L.) Merr.] production is the use of cultivars that produce maximum yield under varying environmental conditions. Farmers can grow two or more cultivars in pure stand or in a mixture to avoid the yield reduction that can occur if one cultivar does not perform as expected.

Research in several crop species has indicated that mixtures of cultivars generally are more stable in yield than a single cultivar (Allard, 1961; Clay and Allard, 1969; Frey and Maldonado, 1967; Pfahler, 1965; Probst, 1957; Rasmusson, 1968; Schutz and Brim, 1971). However, none of the studies have compared the yield stability obtained by growing two or more cultivars in pure stand with that of a mixture of the same cultivars. Probst (1957) indicated that blending of soybeans had a stabilizing effect on yield and seemed to be important for approaching maximum yields each year. Schutz and Brim (1971) found two- and three-component mixtures generally were more stable than pure lines, with the degree of stability apparently dependent upon the competitive interaction involved. None of the research in soybeans have involved mixtures with more than three components.

The objective of this study was to determine how many high-yielding soybean cultivars should be grown either in pure stand or in a mixture to obtain high yield and stability across environments.

LITERATURE REVIEW

The Theory of Stability

The stability of production of crop cultivars under varying environmental conditions has been the subject of considerable research. Stability has been used to describe the homeostatic reaction of a genotype or population. The term "homeostasis" was proposed originally by Cannon (1932) to describe the ability of an organism to maintain constancy in fluctuating environments. The concept of homeostasis was discussed in detail by Lerner (1954). He suggested that the degree of adaptiveness of either individuals or groups in cross-fertilized species may be a function of their degree of heterozygosity, whereby heterozygotes are more highly buffered in their developmental processes than are homozygotes. Lerner was concerned that any selection, other than natural selection, would reduce homeostatic control within and among genotypes of a species.

Lewontin (1957) considered two types of homeostasis within a population. First, the genotypic composition of the population may be flexible, and second the individuals themselves may be homeostatic. The former was referred to as populational homeostasis and was based upon genetic diversity within the population, whereas the latter was called individual homeostasis and may exist in genetically homogeneous populations.

Simmonds (1962) used the term "adaption" for describing the functions of homeostasis. He divided adaption into four categories:

specific-genotypic, general-genotypic, specific-population, and general-population adaption. Specific-genotypic was defined as the adaption of a single line or clone to a limited environment. General-genotypic adaption referred to the capacity of a genotype to produce a range of phenotypes adapted to many different environments. Specific-population adaption was defined as the specific adaption of a heterogeneous population which is attributable to interactions among components rather than to the adaption of the components themselves. This may be a property of populations composed of mixtures of genotypes. An example is the superior performance of a mixture relative to the mean of its components. General-population adaption was defined as the capacity of a heterogeneous population to adapt to many different environments. Simmonds (1962) cited evidence that mixtures should have stability because of their heterogeneity.

"Individual buffering" and "populational buffering" were terms used by Allard and Bradshaw (1964) to describe the methods of stabilizing performance in fluctuating environments. A stable cultivar may be made up of a number of genotypes each adapted to a somewhat different range of environments, or the individuals themselves may be well buffered so that each member of the population is well adapted to a range of environments. Individual buffering may be a property of specific genotypes and not associated with heterozygosity, or it may be attributable to the heterozygosity of hybrid individuals. Populational buffering depends upon the heterogeneity of coexisting genotypes. They concluded that genetic diversity, either in heterozygotes or in mixtures of different genotypes, often leads to stability under varying environmental conditions. Allard and Hansche (1964) in a review article cite many examples of individual and populational buffering.

Stability of Mixtures

Considerable evidence exists that heterogeneity contributes to populational homeostasis. Consequently, the use of mixtures rather than pure lines has been suggested as a means of reducing genotype x environment interaction. Jensen (1952) suggested multiline cultivars could supplement the production of new pure line cultivars. Multiline cultivars theoretically should possess a longer productive life, greater stability of production, broader environmental adaption, and greater protection against diseases than pure line cultivars.

Allard (1961) studied the relationship between genetic diversity and consistency of performance in different environments for lima beans. He compared pure lines, two-component mixtures, three-component mixtures, and bulk populations from hybrids of the pure lines. Pure lines were found to be less stable in productivity than the mixtures or bulks. Only small differences in stability were observed among the mixtures and bulks. He concluded that genetic diversity endowed the populations with stability irrespective of the number and component genotypes involved.

Frey and Maldonado (1967) found that oat mixtures of two to five components were more stable for grain yield than pure lines when tested at two planting dates for three years. Pfahler (1965) showed yields of oat mixtures and rye mixtures were less than or equal to the yields of the higher yielding, component pure lines. Variability over years for oat mixtures and rye mixtures was appreciably lower than the mean of the component pure lines. Qualset and Granger (1970) compared the stability of two oat cultivars with their mixtures over 10 environments. The mixtures had smaller deviations from regression than the pure line cultivars and were considered to be more stable.

Reich and Atkins (1970) evaluated the yield stability in nine environments of four types of grain sorghum populations: parental lines, F_1 hybrids, two-component mixtures of parental lines, and two-component hybrid mixtures. Hybrid mixtures were the most productive and stable, although none of the population types were distinctly superior for all parameters. Hybrid mixtures had the highest mean yield and an average regression coefficient near one, but they were second to parental mixtures in terms of low deviations from regression. Some single-cross hydrids were as stable as any of the mixtures, indicating that good stability through individual buffering is attainable in single-cross sorghum hybrids.

Funk and Anderson (1964) reported that mixtures of two or more corn hybrids, either in the same hill, in alternate hills, or in alternate rows, did not result in yields that were significantly different from the mean of the component hybrids grown separately. However, mixtures were found to increase yield stability, as indicated by a decrease in the entry x location interaction.

Smith, Byth, Caldwell, and Weber (1967) determined the stability of yield across six environments for soybean cultivars, F_2-derived lines, and F_5-derived lines. In general, no differences were observed between regression coefficients for the three types of lines. F_5-derived lines had larger deviation mean squares than the F_2-derived lines and the adapted check cultivars had smaller deviation mean squares than either the F_2-derived or F_5-derived lines. The F_2-derived and F_5-derived lines were random samples of the populations and should have depended on individual buffering to the same degree. The greater stability of F_2-derived lines could be attributed to populational buffering. The lower deviation mean squares for the check cultivars were probably due to the cultivars being better adapted to the environments because the cultivars had been selected on the basis of extensive yield testing.

Byth and Weber (1968) reported on the effects of degrees of genetic heterogeneity within soybean populations on genotype x environment interaction. They evaluated two random and unselected populations of genetically heterogeneous F_2-derived, and homogeneous F_5-derived soybean lines in three environments. F_2-derived lines revealed no yield advantage but did reveal a greater phenotypic stability across environments than F_5-derived lines as indicated by the genotype x environment variance component. This was related to the degree of genetic heterogeneity in the F_2-derived lines.

Probst (1957) evaluated three soybean cultivars and 18 mixtures and found mixtures had no superiority in yield over the highest yielding component cultivar in any of the four years of testing. There was a significant cultivar x year interaction for seed yield and he reported blending of soybeans had a stabilizing effect on yield.

Schutz and Brim (1971) compared the yield stability of four soybean cultivars, six two-component mixtures, and four three-component mixtures. Mixtures generally were more stable than pure lines with the degree of stability dependent upon the type of competitive interaction involved. Overcompensatory and complementary interactions seemed to be essential for stability of performance of a heterogeneous population.

Rasmusson (1968) compared the stability of yield of six barley pure lines, six two-component mixtures, two three-component mixtures, and six bulk hybrids over 10 environments. Cultivars, two-component, and three-component mixtures were judged to be similar in stability but were less stable than the bulk hybrids. Differences among entries within each of the groups were relatively large and precluded definite conclusions regarding the relationship between level of heterogeneity and stability.

Clay and Allard (1969) compared the yield stability of 10 cultivars, 13 two-component, two three-component, five four-component, two five-component, and one 10-component mixture across 10 environments. The mixtures had a small advantage in yield over the average of the component cultivars. The number of components in a mixture appeared unrelated to yield and regression coefficients. Deviations from regression decreased as level of heterogeneity increased. Two cultivars were found which had regression coefficients not significantly different from one and nonsignificant deviation mean squares. These cultivars were as stable as any mixture.

Busch, Hammond, and Frohberg (1976) compared the yield stability of F_2 and F_3 bulks with their elite parental lines of hard red spring wheat. They found little advantage for heterogeneous populations over pure lines as measured by regression coefficients and deviation mean squares.

Marshall and Brown (1973) theorized that the plant breeder interested in achieving increased stability through the use of mixtures will be able to predict the potential stability of a mixture from the mean variance and covariance in yield of the components grown in pure stand. Reich and Atkins (1970) found regression coefficients of sorghum mixtures could be predicted from mixture-component data, and Hanson (1970) suggested stable soybean mixtures can be produced by choosing stable genotypes for the mixture.

In summary, the literature indicated that mixtures generally yield less than their best component and are more stable than the mean stability of their components. Mixtures of highly adapted cultivars are often less stable than their best component. In general increasing heterogeneity of mixtures had little effect on the linear response to environments. Stable mixtures can be produced by choosing stable pure lines for the mixture.

Stability of Pure Lines

There is considerable variability for yield stability among pure lines. This stability is dependent upon individual buffering in the pure line. Finlay and Wilkinson (1963) grew 277 randomly chosen barley cultivars in nine environments in Australia. They characterized cultivars with high mean yields and regression coefficients of one as being well adapted to all environments. Certain cultivars had regression coefficients significantly greater than one. Those cultivars had a sensitivity to environmental change and were adapted to high-yielding environments. Certain cultivars had regression coefficients significantly less than one. Those cultivars were resistant to environmental change and were better adapted to low-yielding environments. Cultivars from particular geographic regions of the world showed a similarity in type of adaption.

Quisenberry and Kohel (1971) studied the effects of ploidy on phenotypic stability of cotton and compared the stability of parental lines and F_1 hybrids over a range of environments. They found a diploid species that had as much stability as either of two allotetraploid species.

Johnson, Shafer, and Schmidt (1968) conducted a regression analysis on hard red winter wheat yields in the Northern and Southern Regional Performance Trials from 1937 to 1960. They found the yield relationship of cultivars based on linear regressions from three years of data were very similar to those projected from 24 years of testing. Thus stability information on wheat cultivars can be compiled from as little as three years of regional testing. The yields of cultivars based on their linear regressions indicated that both improved stability and higher yields have been achieved for recently developed cultivars.

Joppa, Lebsock, and Busch (1971) performed regression analysis using yields from Uniform Spring Wheat Nurseries grown at 15 to 20 locations in the North Central United States and Canada in each of 10 years (1959-1968). Each cultivar tended to have its own characteristic regression coefficient and deviations from regression. The large deviations for some cultivars were associated with specific genotype x environment interactions, such as susceptibility to a particular disease or partial sterility. They concluded regression analyses on uniform regional data could assist plant breeders in making decisions regarding cultivar release.

Smith, Byth, Caldwell, and Weber (1967) evaluated the stability and yield of 19 pure line genotypes from the 1962 and 1963 Northern States Uniform Group I and II Tests. Regression coefficients ranged from 0.85 to 1.18 and genotypes with a high mean yield generally had a regression coefficient greater than 1.00. Only one genotype had a significant deviation mean square.

Baihaki, Stucker, and Lambert (1976) conducted a study to determine if genotype x environment interaction in preliminary yield tests of soybeans was associated with the yield level of the lines. Lines were tested in six environments and categorized into high, medium, and low-yielding groups. About 50% of the total genotype x environment interaction for yield was contributed by the low-yielding group, 25% by the medium-yielding group, and 25% by the high-yielding group.

In summary, the literature indicated that pure lines grown over many environments will be characterized by their own relative stability parameters. Yield testing over many environments with selection for high yield should improve the average level of stability of pure lines.

Stability of Hybrids

A single cross is a genetically homogeneous population and must depend entirely on individual buffering for its stability of production. Three-way and double crosses may have stability resulting from heterogeneity within the population. A number of studies have been conducted to evaluate yield stability of various types of hybrids across a range of environments and to investigate the relative importance of individual and populational buffering.

Sprague and Federer (1951), Jones (1958), and Eberhart, Russell, and Penny (1964) reported that hybrid x environment interactions were much greater for single crosses of maize than for three-way or double crosses. Eberhart and Russell (1966) compared the stability of two sets of single-cross diallels and a set of three-way crosses in maize. They obtained significant differences among hybrids for regression coefficients. Estimates of deviations from regression ranged from near zero to extremely large values for different hybrids. Similar results were found in another study (Eberhart and Russell, 1969), where single crosses were compared with double crosses. In both studies single crosses as a group were less stable; however, single crosses were found that were as stable as any three-way or double cross.

Weatherspoon (1970) compared single, three-way, and double crosses involving unrelated inbred lines of maize in four environments. The single crosses had the highest average yields followed by three-way crosses and the double crosses. The hybrid x environment mean square for single crosses was more than twice that for the double crosses, whereas the three-way crosses had an intermediate interaction mean square. He concluded that in general single crosses were more sensitive to varying environments than were the three-way or double crosses. High-yielding, stable single crosses were observed and he suggested that wide scale testing is essential to select those single crosses with high yield and stable performance.

Collins, Russell, and Eberhart (1965) proposed that second-ear development on maize hybrids may be a mechanism that would contribute to stability. Russell and Eberhart (1968) investigated the yield response and stability of testcrosses of one- and two-ear inbreds. The two-ear characteristic had a stabilizing effect on yield in different environments. The regression coefficients of two-ear hybrids were less than one, indicating that the two-ear characteristic gave relatively better performance in lower yielding environments.

Scott (1967) selfed individual F_2 plants from two maize single crosses and crossed them to a single-cross tester. Yields from six environments were used to compute an environmental variance for each entry. Three groups of F_2's with high, medium, and low environmental variances were selected from each source of material. Testcrosses involving the group with low environmental variances had significantly lower regression coefficients than testcrosses from the other groups. The results indicated that selection for yield stability may be effective.

Falck (1970) investigated the relationship among levels of heterogeneity and yield stability for elite maize materials. Five types of crosses in order of heterogeneity were single crosses, related-line double crosses, three-way crosses, double crosses, and synthetic crosses. Each cross was represented by five hybrids that were selected on the basis of high yield performance in earlier tests. The results of the yield trials over 12 environments indicated that a hybrid's regression coefficient and deviations from regression were not related to its level of heterogeneity. The results indicated that individual buffering capacity was of a greater magnitude than populational buffering capacity in maize when hybrids were selected according to high yield performance.

Finlay (1963) evaluated the stability of hybrid populations of barley. F_2 seed of 45 F_1 hybrids and their 10 parents were yield tested for three years. The hybrid populations had greater yields and smaller regression coefficients than the parental cultivars. Most of the parental cultivars had regression coefficients greater than one, whereas most of the hybrids had regression coefficients less than one. Thus the superiority of hybrids over their parents was particularly manifested in the lower yielding environments.

Jowett (1972) performed a yield stability analysis on single crosses, three-way crosses, and inbred cultivars of grain sorghum in eight locations in East Africa. The hybrids had larger regression coefficients than the inbreds and were more stable than the inbreds. There was no difference in the mean regression coefficients of three-way and single crosses. Smaller deviations from regression were obtained for the three-way crosses than for the single-crosses, but differences between the two types were small. Certain single crosses were found to have very small deviations from regression suggesting individual buffering may be of considerable importance.

Walsh and Atkins (1973) compared the yield variability over two years of sorghum single crosses and three-way crosses. Comparison of the hybrid type x year mean squares indicated that three-way crosses on the average had greater stability of performance than single crosses. However, this did not preclude that some single crosses could be as stable as the most stable three-way cross.

Patanothai and Atkins (1974) conducted yield trials over nine environments to compare the stability of parental lines and their hybrids to a range of environmental conditions. Single crosses and three-way crosses had equivalent yields and both hybrid types yielded significantly more than parental lines. Deviations from regression were smaller for three-way crosses and their average regression coefficient was close to one. Therefore, three-way crosses as a group were slightly more stable for grain yield than the single crosses. Considerable variation for these parameters was evident among the individual hybrids suggesting that stability of performance may be attainable with either single or three-way crosses.

In summary, the literature indicated that in general three-way and double crosses, which have individual buffering and populational buffering, are more stable than single crosses. However, single crosses have been identified which are as stable as any three-way or double cross.

This shows the important contribution of individual buffering. There was evidence that certain hybrids selected on the basis of high yields across a wide range of environments may have considerable stability.

Methods of Stability Analysis

There are many recent review articles and research papers that compare the different methods of stability analysis (Easton and Clements, 1973; Freeman, 1973; Freeman and Perkins, 1971; Moll and Stuber, 1974; Mungomery, Shorter, and Byth, 1974; Perkins and Jinks, 1968; Shukla, 1972; and Tai, 1971). Mean yield in different environments was the first parameter used for measuring adaptation of genotypes. The second parameter used to measure the response of a genotype to environmental variation was the regression coefficient proposed by Yates and Cochran (1938). Finlay and Wilkinson (1963) used this technique to study the adaption of barley cultivars obtained from the world collection. For each cultivar a linear regression of cultivar mean yield on an environmental index was computed to measure cultivar adaption. They considered that absolute phenotypic stability would be expressed by a regression coefficient of zero.

Eberhart and Russell (1966) proposed a third parameter, deviations from regression. They considered regression coefficients and deviations from regression as important components of the genotype x environment interaction. A regression coefficient and deviations from regression were determined for each entry. In their analysis sums of squares for environments and genotype x environment interaction were added together and repartitioned into a linear component among environments, a linear component of the genotype x environment interaction, and deviations from regression. The trouble with this approach, as pointed out by Freeman and Perkins (1971), is that the sum of squares for the linear component among environments which is allocated one degree of freedom, is the same as the total sum of squares for environments. They defined a stable genotype as one with a regression coefficient of one and no deviations from the regression line.

Perkins and Jinks (1968) partitioned the genotype x environment interaction into components due to heterogeneity among regressions and deviations from regression. This particular approach, which also gives a regression coefficient and deviations from regression for each entry, is commonly known as the joint regression analysis.

Parameters similar to the regression coefficient and deviations from regression can be obtained by structural relationship analysis (Tai, 1971). These parameters differ only slightly from the regression coefficient and deviations from regression when the number of genotypes or range of environments is large.

The above papers used the mean performance of all genotypes in an environment to establish indexes of environmental productivity. Freeman and Perkins (1971) suggested environmental indexes should be assessed by a set of check cultivars that are independent from the entries being studied. Fantunla and Frey (1976) compared check cultivars of oats in Iowa, in any number from two to 20, with all entries in the test for establishing environmental indexes and found no differences in relative rankings of the entries. They suggested the use of a standard set of checks would permit direct comparisons between regression stability index values from experiments conducted at different sites in different years.

When only a small portion of the genotype x environment variation is due to heterogeneity among regression coefficients, partitioning the genotype x environment variation into components due to each genotype may be more meaningful than the regression approach. Plaisted and Peterson (1959) calculated a separate analysis of variance for each pair of genotypes and used the mean of the interaction variances involving an individual genotype as a measure of its contribution to the total genotype x environment variance. Plaisted (1960) conducted an analysis of variance for all genotypes and then recalculated the analysis of variance omitting one genotype. The process was repeated for all genotypes and the genotypes which gave the largest reduction in the genotype x environment interaction were considered stable. Wricke (1962) used a method called ecovalence, which was the contribution of a genotype to the genotype x environment interaction sum of squares. Partitioning of the interaction was non-orthogonal and had undesirable statistical properties (Freeman and Perkins, 1971). Shukla (1972) partitioned the genotype x environment variance into individual genotype components which he called stability variances. Hanson (1970) used a stability measure that was similar to Wricke's, but took into account regression. In this method the environmental response does not have to be linear as in regression methods but may be parabolic or any other response form specified.

When genotype x environment interactions are very large, a multivariate technique may be useful (Freeman, 1973). Mungomery, Shorter, and Byth (1974) used a cluster analysis to study adaption of soybean cultivars from around the world to the south-eastern Queensland of Australia. They were able to identify several groups of lines which varied in their response across environments. Unlike other analyses, this method required no prior assumption regarding the distribution and suitability of a particular environmental response.

In summary, some methods are not very easy to use while others are not as statistically correct. The best use of certain methods depends on the magnitude of the genotype x environment interaction or on the portion of the genotype x environment interaction attributable to the linear response to the environment.

MATERIALS AND METHODS

Formation of Mixtures

Twenty-eight cultivars and experimental lines were selected for high yield from the 1974 Northern States Uniform Soybean Test. Selection of lines was restricted to a 10-day range in maturity. The 28 soybean lines and their maturities relative to Corsoy are given in Table 1. These soybean lines were used to form 80 entries representing 12 levels of heterogeneity. The level of heterogeneity depended on the number of component pure lines in the entry. To meet the objective of this research the entries were prepared either from 14 pure lines or 28 pure lines (Table 2). The yield and maturity range was the same for the 14 pure lines and the 28 pure lines. Seed mixtures with two to 14 components were prepared from the 14 lines grown in pure stand to permit a comparison of mixtures with their components. The other 14 lines were used to prepare more diverse seed mixtures, particularly with 12 and 14 components. The mixtures were prepared by randomly selecting the desired number of components from the 14 or the 28 lines. The only restriction on selection for each level of heterogeneity was that once a line was used it could not be chosen again until all the other lines had been selected. An equal number of viable seeds from each component were mixed together for each plot and the mixtures were reconstituted for each year of testing.

Table 1. Soybean lines and their maturity compared with Corsoy

Line number	Line name	Maturity[a]
1	M68-48	-3
2	A73-22031	-4
3	Coles	-1
4	A73-22056	-2
5	M68-96	-1
6	A73-137	+1
7	Corsoy	0
8	L71-2322	+3
9	A73D-13	+6
10	A73-13078	+3
11	A73-25088	+5
12	L72A-14	+6
13	Wells	+2
14	Amsoy 71	+3
15	M68-94	-3
16	A73-19068	-2
17	A73D-16	-1
18	L71-2033	-2
19	Hark	-2
20	L70-3127	0
21	L71-2071	0
22	L70-2891	0
23	A73-225	+1
24	Marion	+6
25	A73-22051	+5
26	Harcor	+2
27	Beeson	+6
28	L70D6-16	+5

[a]Days earlier (-) or later (+) than Corsoy.

Experimental Procedures

The eighty entries were evaluated at six locations throughout Iowa in 1975 and 1976 in a randomized complete-block design with two replications per location. The locations, planting dates, and mean yields for each environment are given in Table 3. These environments are

Table 2. Composition of the 80 entries grown for yield evaluation

Number of components in entry	Number of entries prepared with 14 lines	Number of entries prepared with 28 lines	Total
1	14	0	14
2	3	3	6
3	3	3	6
4	3	3	6
5	3	3	6
6	3	3	6
7	3	3	6
8	3	3	6
9	3	3	6
10	3	3	6
12	3	3	6
14	1	5	6
			80

representative of the soil and climatic factors encountered in northern, central, and southern Iowa. Plots consisting of four rows 69 cm apart and 4.6 m long were planted with 26 viable seeds per meter of row. All plots were cultivated and hand weeded. A 3.0 m section of the two center rows in each plot was harvested for yield when the seed had 15% moisture or less. To evaluate all plots at the same moisture,

Table 3. Location, date of planting, and mean yield of environments

Location	Date of planting	Mean yield[a] (q/ha)
Ames	May 12, 1975	39.2 a
Kanawha	May 10, 1975	35.0 b
Sloan	May 19, 1975	34.4 b
Ottumwa	May 21, 1976	33.7 bc
Spencer	May 22, 1975	31.8 cd
Corwith	May 11, 1976	31.6 cd
Farragut	May 5, 1976	30.7 d
Sloan	May 4, 1976	26.9 e
Ames	May 7, 1976	22.6 f
Spencer	May 10, 1976	20.8 fg
Ottumwa	May 15, 1975	19.3 g
Farragut	May 5, 1975	11.1 h

[a]Values followed with the same letter are not significantly different from each other at 5% probability level according to Duncan's Multiple Range Test.

the seed was dried at 40 degrees C for 2 days before weighing. Seed yield was recorded in grams per plot and converted to quintals per hectare.

Statistical Procedures

A combined analysis of variance across locations and years was conducted using a randomized complete-block design model (Cochran and Cox, 1957). Location, year, and entry effects were considered to be random. Entries were considered random because the mixtures were prepared by randomly selecting components from among the 14 or 28 lines. The general model for v entries grown in l locations and y years with r replications in each environment can be represented by $Y_{ijk} = \mu + v_i + l_j + y_k + (ly)_{jk} + r_{(jk)m} + (vl)_{ij} + (vy)_{ik} + (vyl)_{ijk} + e_{ijkm}$ where: $i = 1, 2, \ldots, 80$; $j = 1, 2, \ldots, 6$; $k = 1, 2$; and $m = 1, 2$.

The sums of squares for entries and first- and second-order interaction with entries were partitioned into among and within levels of heterogeneity. The error terms associated with among and within levels of heterogeneity were calculated separately and evaluated for homogeneity by a two-tailed F test. The error variances were not homogeneous so the error terms for among and within levels of heterogeneity were used in the appropriate F tests. The within levels of heterogeneity sum of squares was partitioned into components for each level of heterogeneity. The individual error variances for each level of heterogeneity were homogeneous according to Bartlett's test, as outlined by Steel and Torrie (1960); therefore, the within levels of heterogeneity error term was used in the appropriate F tests. Estimates of variance components and their standard errors were determined as outlined by Comstock and Moll (1963). Significance of the various components was determined using the appropriate F test.

Satterthwaithe's (1946) method of approximating degrees of freedom was used when mean squares were combined.

To determine if any differences for yield occurred between pure lines and mixtures, entries and the first- and second-order interactions were partitioned into components of pure lines versus mixtures, among pure lines, and among mixtures. The among pure lines mean square was significant so a Duncan's Multiple Range Test was conducted on entry means.

A joint regression analysis for seed yield was calculated from the model of Perkins and Jinks (1968): $Y_{ijk} = \mu + d_i + \varepsilon_j + r_{jk} + \beta_i\varepsilon_j + \lambda_{ij} + e_{ijk}$, where Y_{ijk} is the yield of the ith soybean entry in the kth replication of the jth environment, μ is the overall mean, d_i is the contribution of the ith entry, ε_{jk}, the environmental index, is the mean of all entries at the jth environment minus the grand mean, r_{jk} is the contribution of the kth replication in the jth environment, β_i is the linear regression coefficient for the ith entry, λ_{ij} is the deviations from regression, and e_{ijk} is the residual variation of ith entry in the kth replication of the jth environment.

In the joint regression analysis the entry x environment interaction is partitioned into components due to heterogeneity among regressions and deviations from regression. Heterogeneity among regressions and deviations from regression sums of squares were partitioned further into among and within levels of heterogeneity. The mean squares for heterogeneity of regressions and deviations from regression were tested against the pooled error to determine whether observed differences between entries could be accounted for by a linear effect of environments (Freeman and Perkins, 1971).

For each entry two parameters were used to describe stability across environments. The regression coefficient $(1 + \beta_i)$ and the deviation mean square $\sum_j \delta_{ij}^2/(s-2)$ can be obtained directly from the preceding model by least squares. The least square estimates are obtained as

$$1 + \beta_i = \frac{\sum_j \bar{Y}_{ij.}\ \varepsilon_j}{\sum_j \varepsilon_j^2} \qquad \text{where} \qquad \bar{Y}_{ij.} = \sum_k \frac{Y_{ijk}}{r} \ .$$

The deviation sum of squares is obtained as

$$\sum_j \delta_{ij}^2 = \sum_j (\bar{Y}_{ij.} - \bar{Y}_{i..})^2 - \frac{(\sum_j {}_{ij.}\ \varepsilon_j)^2}{\sum_j \varepsilon_j^2}$$

$$\text{where} \qquad \bar{Y}_{i..} = \sum_j \sum_k \frac{Y_{ijk}}{rs} \ .$$

A stable entry is defined as having a regression coefficient not significantly different from unity and deviations from regression close to zero. A high mean yield also is desired although it is not necessarily an indicator of yield stability.

Each regression coefficient was tested to determine if it was different from unity using a t test, where $t = (b_i - 1)/S_{\bar{b}_i}$. The test of significance for the deviation from linear response to the different environments was made for each entry with an F test, by dividing the deviation mean squares by the pooled error. The mean yields, regression coefficients and deviation mean squares were each regressed on the level of heterogeneity to determine if any relationship existed.

The stability of mixtures was compared with the stability of the component pure lines as multiple pure stands. The average deviation mean square for components of mixtures (Figure 1, B) did not properly estimate the deviation mean squares for multiple pure stands. Such an estimate fluctuated around the average deviation mean square for pure lines and ignored the fact that an average yield of two or more lines in pure stand reduced the effect of an unusually high or low yield for one or more of the lines, thereby, reducing the deviation mean square. A more valid estimate of deviation mean squares for multiple pure stands was obtained by averaging for each replication in each environment the pure stand yields of components in each mixture. The component means were used to compute regression coefficients and deviation mean squares with the same environmental index used for all 80 entries. This estimate (Figure 1, C) was considerably smaller than the deviation mean squares for mixtures (Figure 1, A), because of the influence of the number of component pure lines. The deviation mean square (δ_{ij}) has variation due to deviations from regression (λ_{ij}) and residual variation of the ith entry in the kth replication of the jth environment (e_{ijk}) so that $\delta_{ij} = \lambda_{ij} + \sum_k e_{ijk}$. The value of k for any mixture is 2 and for a component mean is 2 x n where n is the number of component pure lines in a mixture. The value of $\sum_k e_{ijk}$ decreases as a function of n and is zero when $k = \infty$. Therefore, each deviation mean square for multiple pure stands (Figure 1, C) was multiplied by n (Figure 1, D) to permit

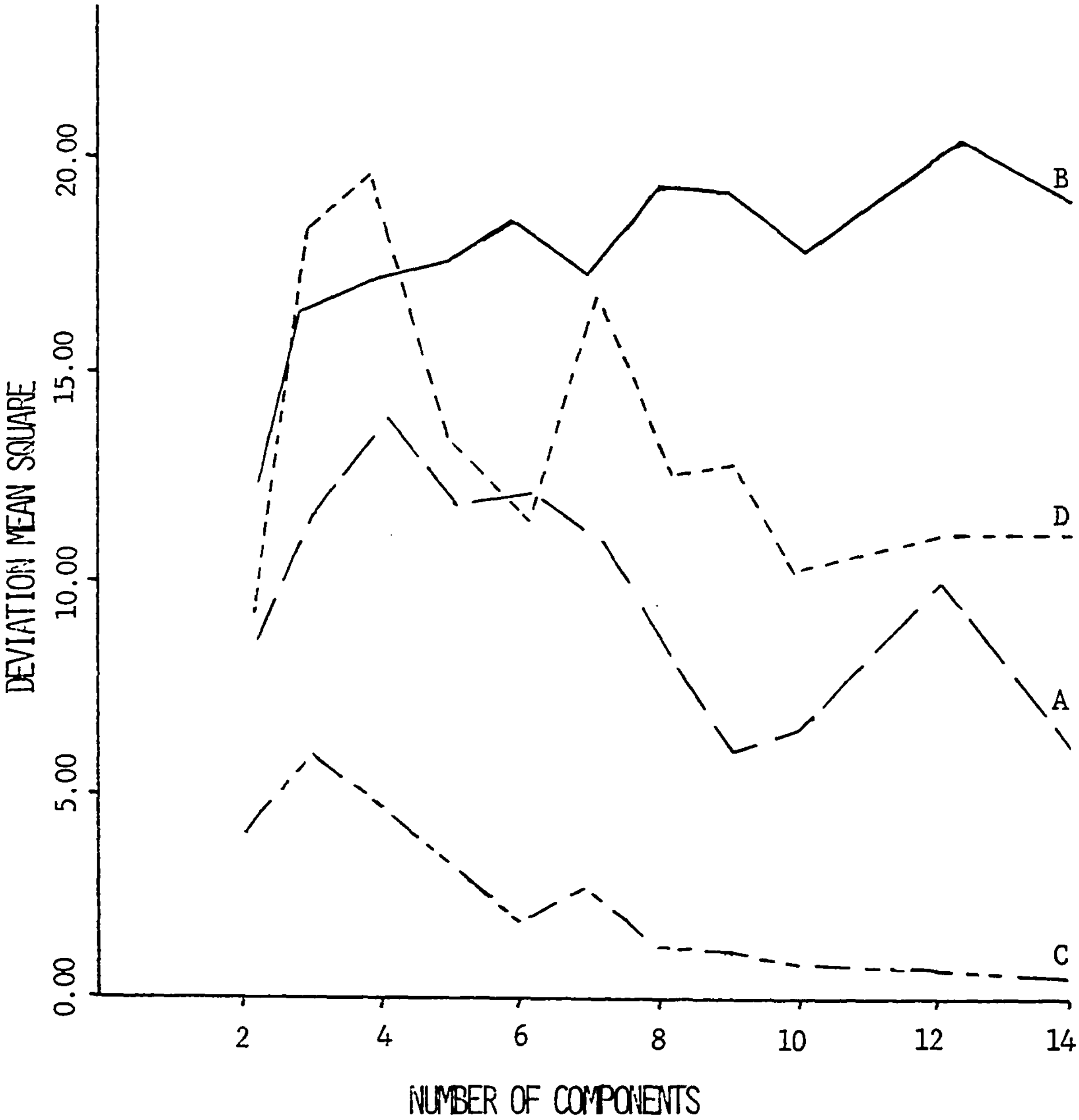

Figure 1. (A) Average deviation mean squares for mixtures with two to 14 components, (B) mean deviations of the component pure lines, (C) average deviations for multiple pure stands of the component pure lines, and (D) average deviations for multiple pure stand times the number of components at each level of heterogeneity

a direct comparison with deviation mean squares for mixtures. The corrected deviation mean squares for multiple pure stands may be under-estimated since the environmental index was determined by all entries in the test and not independent lines.

A number of t tests were conducted to identify significant differences between mixture and multiple pure stand yields and regression coefficients. For yields

$$t = \frac{|\bar{X}_A - \bar{X}_B|}{\sqrt{\frac{E}{m} + \frac{E}{mn}}} ,$$

where $\bar{X}_A$ was the mixture yield, $\bar{X}_B$ was the yield for multiple pure stands, E was the error mean square for entries, m was the number of values in each mean, and n was the number of components in the entry. For regression coefficients

$$t = \frac{|b_A - b_B|}{\sqrt{S_{\bar{b}_A}^{2} + S_{\bar{b}_B}^{2}}} ,$$

where b_A was the mixture regression coefficient, b_B was the regression coefficient for multiple pure stands, $S_{\bar{b}_A}^{2}$ was the standard error for b_A, and $S_{\bar{b}_B}^{2}$ was the standard error for b_B. A two-tailed F test was used to test for significant differences between deviation mean squares for mixtures and deviation mean squares for multiple pure stands.

RESULTS

Heterogeneity and Yield Stability

Combined analysis of variance

The combined analysis of variance for the yield of 80 soybean entries tested at six locations in 1975 and 1976 is presented in Table 4. Location x year, replication within location x year, entry, and entry x location x year sources of variation had significant mean squares.

The average yields for the six locations were not significantly different nor were the average yields in 1975 and 1976. The location x year mean square was considerably greater than the mean square for either locations or years, which indicated that the relative yield of locations was different among years. When the six locations and two years were considered as 12 environments, the combined analysis indicated that environments were significantly different with a range from 11.1 to 39.2 q/ha and an average of 28.1 q/ha (Table 3). This range adequately covers the levels of productivity commonly encountered for soybeans grown in Iowa. An analysis for stability is most meaningful if the environments have a wide range and a good distribution within this range. The environments in this study were considered highly desirable for evaluating yield stability of the entries.

Table 4. Combined analysis of variance for yield of 80 entries tested at six locations in two years

Source of variation	Degrees of freedom		Mean square (q/ha)
Location	5		6,314.8
Year	1		287.1
Location x year	5		16,861.3**
Replication/location x year	12		108.7**
Entry	79		17.8*
Among[a]		11	15.8
Within[b]		68	18.1*
Entry x location	395		12.3
Among x location		55	9.5
Within x location		340	12.7
Entry x year	79		11.1
Among x year		11	6.2
Within x year		68	11.9
Entry x location x year	395		11.4**
Among x location x year		55	10.6
Within x location x year		340	11.6**
Pooled error	948		8.8
Among		132	11.5
Within		816	8.4
Mean			28.1
Coefficient of variation (%)			10.6

[a]Among levels of heterogeneity.

[b]Within levels of heterogeneity.

*, **F values are significant at 5% and 1% probability levels, respectively.

There were significant differences for average yield among the 80 entries with a range of 25.8 q/ha to 29.9 q/ha. The sum of squares for entries was partitioned into components due to among and within levels of heterogeneity. Levels of heterogeneity were determined by the number of component pure lines in each entry. Among levels of heterogeneity mean square was not significant; therefore, average yields for the 12 levels of heterogeneity were not significantly different from each other (Table 5). The within levels of heterogeneity sum of squares was partitioned into components attributable to each level of heterogeneity. Variance components and their standard errors were estimated (Table 5). A significant variance component occurred only for pure line entries which had the widest range in yield. The yields and maturities of the 14 pure lines are given in Table 6. The lowest yielding pure lines were the earliest to mature.

Entry sum of squares was partitioned to determine whether the average yield of pure lines was different from the average yield of mixtures and to determine whether yields among pure lines and among mixtures were different (Table 7). The average yield of the pure lines (27.8 q/ha) was not significantly different from the average yield of the mixtures (28.1 q/ha). Significant differences did occur among pure lines, but no significant differences occurred among the mixtures.

The regression of entry yields on the number of component pure lines had a slope near zero and showed that the level of heterogeneity had no influence on entry yield (Figure 2). The figure also illustrated

Table 5. Yield and variance components with their standard errors among 14 pure lines and six mixtures for each of 11 levels of heterogeneity

Number of component pure lines	Yield (q/ha)			Variance component
	Mean[a]	Low entry	High entry	σ^2_E
1	27.8	25.8	29.9	0.8 ± 0.6*
2	28.3	27.4	29.6	0.2 ± 0.4
3	28.1	27.3	29.0	0.1 ± 0.2
4	27.7	26.3	28.8	0.3 ± 0.5
5	28.4	26.6	29.3	0.5 ± 0.5
6	28.1	28.2	29.6	0.2 ± 0.4
7	27.8	26.8	28.6	0.0 ± 0.2
8	27.9	27.2	28.3	0.0 ± 0.1
9	28.6	28.0	29.2	-0.3 ± 0.2
10	27.9	26.7	29.1	0.3 ± 0.3
12	28.4	27.4	29.9	0.3 ± 0.4
14	28.6	28.2	29.2	-0.3 ± 0.1

[a]Mean yields among levels of heterogeneity are not significantly different at the 5% probability level according to the analysis of variance.

*F value is significant at 5% probability level.

that pure lines had a greater range in yield than the mixtures prepared from two- to 14-component pure lines.

The mean squares for entry x location and entry x year were not significant when tested with the entry x location x year mean square.

Table 6. Mean yields and maturities for 14 pure lines

Line name	Yield (q/ha)[a]	Maturity[b]
A73D-13	29.9 a	+6
Corsoy	29.6 a	0
L72A-14	29.0 ab	+6
A73-137	28.5 abc	+1
A73-13078	28.4 abc	+3
Wells	28.2 abc	+2
A73-25088	28.0 abc	+5
Amsoy 71	27.8 abc	+3
L71-2322	27.3 abc	+3
Coles	27.2 abc	-1
M68-96	27.2 abc	-1
M68-48	26.4 bc	-3
A73-22031	26.1 c	-4
A73-22056	25.8 c	-2
Mean	27.8	+1

[a]Values followed with same letter are not significantly different from each other at 5% probability level according to Duncan's Multiple Range Test.

[b]Days earlier (-) or later (+) than Corsoy.

Table 7. Mean squares for pure lines versus mixtures, among pure lines, and among mixtures

Source of variation	Degrees of freedom	Mean square (q/ha)
Pure lines vs. mixtures	1	29.2
Among pure lines	13	36.8*
Among mixtures	65	13.8

*F value is significant at 5% probability level.

Variance components and their standard errors were 0.2 $\pm$ 0.3 for entry x location, 0.0 $\pm$ 0.2 for entry x year, and 1.3 $\pm$ 0.4 for entry x location x year interactions. The relative magnitude of these variance components agree with those obtained by Schutz and Bernard (1967) from the 1954-1956 Uniform Group II Soybean Tests. Partitioning the first order interactions into among and within levels of heterogeneity (Table 4) also resulted in nonsignificant mean squares; therefore, the first order interactions were not used to evaluate relative stability of the pure lines and mixtures. The entry x location x year interaction was significant and its sum of squares was partitioned into among and within levels of heterogeneity. The among levels of heterogeneity x location x year interaction was not significant, indicating that the relative performance of the 12 levels of heterogeneity was consistent across locations and years. Entries within levels of heterogeneity did not have the same relative performance across locations and years as indicated by a significant within levels of heterogeneity x location x year interaction.

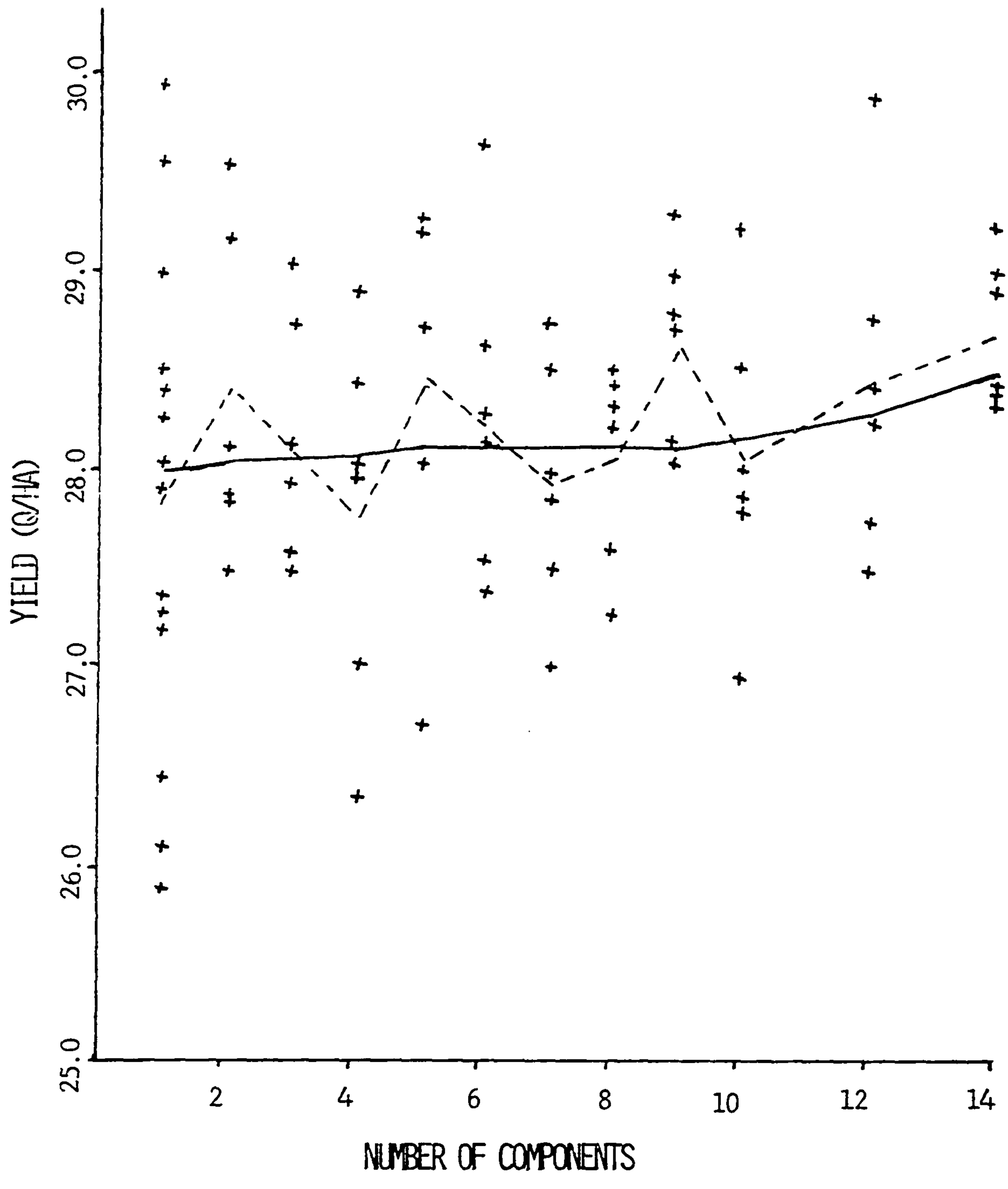

Figure 2. Yields of 14 pure lines and of six mixtures at each level of heterogeneity. The dashed line connects the points representing the mean yield at each level of heterogeneity and the solid line is the regression of yields on number of components ($Y = 27.969 - 0.014X + 0.004X^2$; $R^2 = 0.04$)

An entry x location x year interaction was computed for each level of heterogeneity and significant variance components were obtained for pure lines, two-component, and four-component mixtures (Table 8). Negative variance components obtained for three-, eight-, and 14-component mixtures were assumed to be estimates of zero. The results indicated that relative performance among entries across locations and years tended to be more consistent for the higher levels of heterogeneity.

Analysis of environmental response

A form of the analysis of variance known as the joint regression analysis described by Perkins and Jinks (1968) was used to measure the proportion of the entry x environment variation due to heterogeneity among regression coefficients (slopes of regression lines) and deviations from regression. Regression coefficients and deviation mean squares were determined for each entry. These stability parameters describe the linear and nonlinear relationship, respectively, between entries and environments. The regression coefficient is a measure of the rate of change for entry yields per unit change in the environmental index. The deviation mean square is the average of the squared distances of points from the calculated regression line.

The joint regression analysis is presented in Table 9. It should be noted that the mean squares for environment, entry, entry x environment, and pooled error correspond with their associated mean squares in the combined analysis of variance (Table 4). Regression coefficients ranged from 0.82 to 1.16 and were not significantly

Table 8. Variance components and their standard errors for each level of heterogeneity x location x year interaction

Number of component pure lines	Variance component σ^2_{ELY}
1	2.6 $\pm$ 1.0**
2	3.1 $\pm$ 2.1*
3	-1.6 $\pm$ 1.0
4	5.9 $\pm$ 2.8**
5	2.1 $\pm$ 1.9
6	1.1 $\pm$ 1.6
7	0.6 $\pm$ 1.5
8	-0.9 $\pm$ 1.2
9	2.8 $\pm$ 2.0
10	1.0 $\pm$ 1.6
12	2.2 $\pm$ 1.9
14	-1.2 $\pm$ 1.1

*, **F values are significant at 5% and 1% probability levels, respectively.

different from each other or from 1.00. This indicated that the linear responses of the entries to the different environments were similar. The average regression coefficient for the entries was 1.00 because the environmental index was estimated from the performance of all entries in the test. Regression coefficients were regressed on the number of components in each entry (Figure 3). The regression line had a slope

Table 9. Joint regression analysis for yield stability of 80 entries tested in 12 environments

Source of variation	Degrees of freedom			Mean square (q/ha)
Environment	11			10,560.7**
Entry	79			17.8**
Entry x Environment	869			11.8**
Heterogeneity of regression coefficients		79		10.5
Among[a]			11	6.0
Within[b]			68	11.3
Deviations from regression		790		11.9**
Among			110	10.1
Within			680	12.2**
Pooled error	948			8.8
Among		132		11.5
Within		816		8.4

[a]Among levels of heterogeneity.

[b]Within levels of heterogeneity.

**F values are significant at 1% probability level.

near zero and showed that the level of heterogeneity had no effect on the size of the regression coefficients.

The heterogeneity of regressions sum of squares was not a very large proportion of the entry x environment interaction. As pointed out by Eberhart and Russell (1966), the deviations from regression become very important when linear regressions do not contribute much to the entry x environment interaction. The sum of squares for deviations from regression was partitioned into among and within

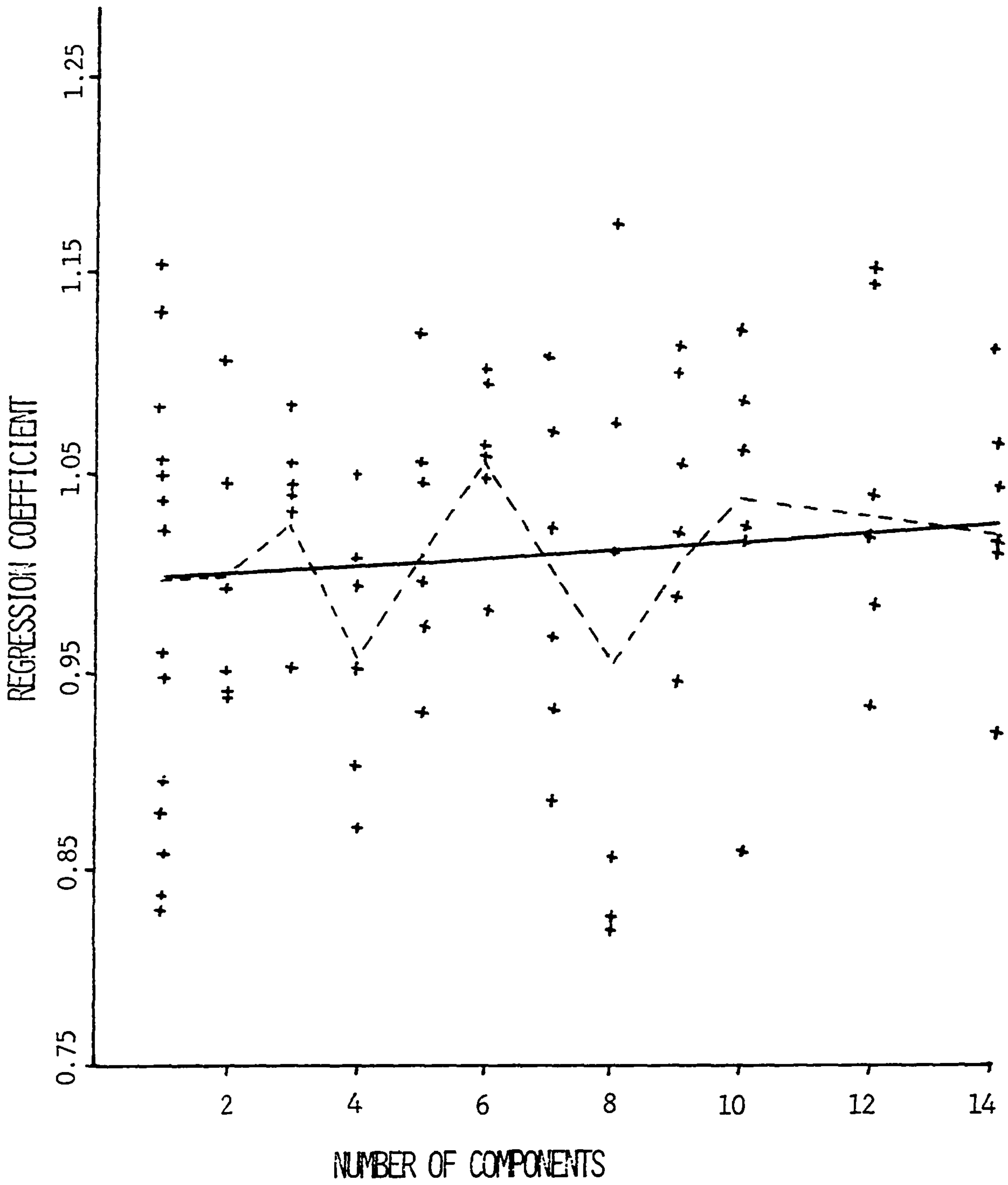

Figure 3. Regression coefficients of 14 pure lines and of six mixtures at each level of heterogeneity. The dashed line connects the points representing the mean regression coefficient at each level of heterogeneity and the solid line is the regression of regression coefficients on number of components ($Y = 0.991 + 0.001X$; $R^2 = 0.01$)

levels of heterogeneity. The mean square for among levels of heterogeneity was not significant, indicating that average deviations from regression were similar for the pure lines and mixtures. The mean square for within levels of heterogeneity was highly significant. Deviation mean squares for each entry were tested against the pooled error and 12 of the 80 entries had deviation mean squares that were significant at the 5% probability level (Figure 4). Five pure lines, one two-component mixture, and one four-component mixture had deviation mean squares that were significant at the 1% probability level. The range in deviation mean squares was greatest for pure lines, followed by two-component and four-component mixtures. The nonlinear stability parameter, deviations from regression, reflects the ability of a line or mixture to respond to a series of environments in a repeatable way and reflects the kind of stability measured by entry x location, entry x year, and entry x location x year variance components.

The regression of deviation mean squares on the number of component pure lines is presented in Figure 4. The best fitting line constructed with linear and quadratic coefficients indicated a decrease in deviation mean squares with increasing levels of heterogeneity up to mixtures with eight components at which point average deviation mean squares and pooled error were equal. The regression line, however, accounted for a very small portion of the total variation ($R^2 = 0.18$). Variability within each level of heterogeneity restricts generalizations concerning the relationship between level of heterogeneity and stability. For example, although pure lines had the highest average

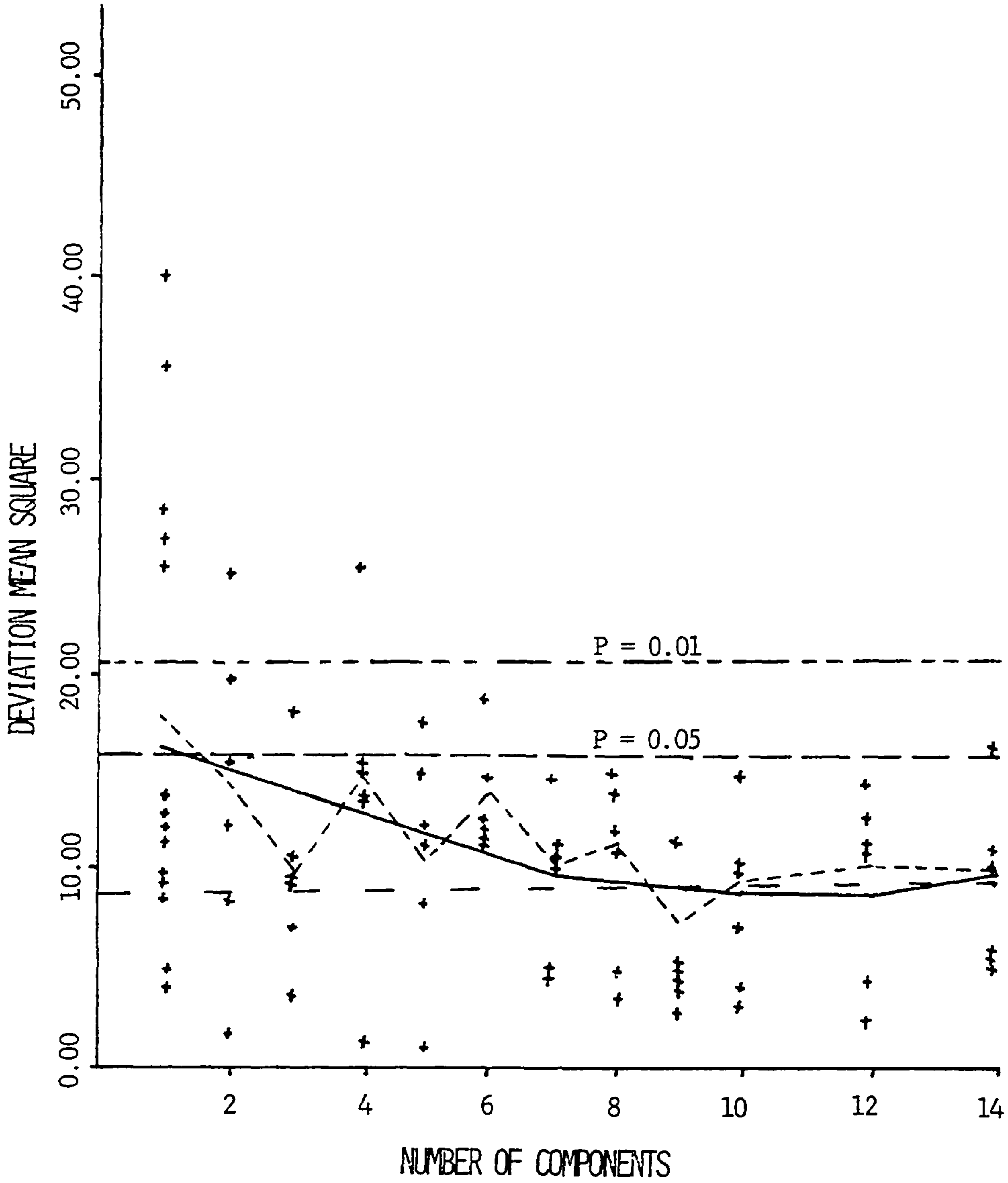

Figure 4. Deviation mean squares of 14 pure lines and of six mixtures at each level of heterogeneity. The dashed line connects the points representing the mean deviation mean square at each level of heterogeneity and the solid line is the regression of deviation mean squares on number of components ($Y = 18.387 - 1.792X + 0.082X^2$; $R^2 = 0.18$)

deviation mean square, nine of the 14 had nonsignificant values indicating that pure lines can be as stable in performance across environments as mixtures.

Mixtures Compared with Multiple Pure Stands

Stability of production for a farmer may be improved by subdividing the production area and growing several cultivars in pure stand instead of a mixture of the cultivars for the entire area. To compare the yield and stability of mixtures with the mean yield and stability of the component pure lines as multiple pure stands, the yields of the component pure line entries for each mixture were averaged for each replication. The mixtures involved in this comparison were those prepared from the 14 lines evaluated in pure stand (Table 6). Mean yields, regression coefficients, and deviation mean squares of multiple pure stands were estimated using a second joint regression analysis.

Mean yields, regression coefficients, and deviation mean squares for 31 mixtures are compared with the estimated mean yields, regression coefficients, and deviation mean squares for multiple pure stands in Table 10. Yields of the mixtures ranged from 4.1% more to 3.7% less than the mean yields of multiple pure stands. There was little yield advantage, an average of 0.4%, for mixtures compared with their component lines in pure stand. The t tests indicated no significant differences occurred between mixture yields and mean yields of multiple pure stands.

Table 10. Comparison of observed mixture values and estimated multiple pure stand values for yield, linear regression coefficients, and deviation mean squares for 31 entries prepared from 14 pure lines

Entry number	Number of component pure lines	Yield[a] (q/ha)		Regression coefficient[a]		Deviation mean square	
		Mixture[b]	Pure[c]	Mixture	Pure	Mixture	Pure
15	2	29.2	29.3	0.98	1.12	12.55	17.51
16	2	27.8	27.7	0.95	0.88	8.76	5.60
17	2	27.8	28.2	0.93	1.05	2.90	3.62
21	3	28.1	27.8	0.95	1.00	7.67*	33.94
22	3	28.7	28.0	1.05	0.98	9.55	5.87
23	3	27.8	27.3	1.04	0.93	18.20	13.66
27	4	28.3	29.0	1.00	1.03	25.01	19.43
28	4	26.3	27.4	0.89	0.96	2.14**	26.08
29	4	28.0	27.7	0.98	1.00	14.06	12.53
33	5	26.6	27.3	0.98	0.94	15.14	6.82
34	5	29.2	28.2	1.11	1.05	11.77	11.22
35	5	28.0	28.0	0.96	0.98	8.25	21.34
39	6	27.3	27.8	1.04	1.01	11.94	14.12
40	6	28.0	27.6	1.05	0.93	12.12	11.81
41	6	27.2	28.0	1.10	1.02	11.98	7.36
45	7	28.4	27.4	1.01	0.94	6.24	16.11
46	7	27.8	27.9	0.95	0.98	15.43	8.06
47	7	26.9	27.8	0.92	0.99	10.31	26.38
51	8	28.0	27.9	1.06	1.00	4.04	12.80
52	8	28.3	27.7	0.82	0.99	14.45	18.29
53	8	28.1	27.7	0.98	0.96	6.01	4.69
57	9	28.0	28.0	0.97	0.99	3.79	6.59
58	9	28.1	28.0	0.98	0.98	6.20	17.43
59	9	28.9	28.0	1.04	0.97	6.58	11.74

[a]No significant differences within columns and between observed mixture values and multiple pure stand values.

[b]Observed mixture values.

[c]Estimated multiple pure stand values based on average pure stand yields for lines in a mixture for each replication.

*, **Deviation mean squares for mixtures and multiple pure stands are significantly different from each other at the 5% and 1% probability levels, respectively.

Table 10. (Continued)

Entry number	Number of component pure lines	Yield[a] (q/ha)		Regression coefficient[a]		Deviation mean square	
		Mixture[b]	Pure[c]	Mixture	Pure	Mixture	Pure
63	10	27.7	28.0	1.01	1.02	9.59	12.36
64	10	27.9	28.1	1.02	1.00	3.93	5.56
65	10	27.7	27.9	1.15	0.99	4.84	11.39
69	12	27.7	27.8	0.99	0.98	10.80	9.22
70	12	28.2	28.0	1.13	1.00	4.48	8.28
71	12	28.6	27.7	1.03	0.98	12.77	14.70
75	14	28.8	27.8	1.04	0.99	5.42	10.53
Mean		28.0	27.9	1.00	0.99	9.58	13.09

The joint regression analysis indicated that none of the regression coefficients of multiple pure stands were significantly different from each other or from 1.00. The t tests indicated no significant differences occurred between regression coefficients of mixtures and multiple pure stands. Therefore, the linear response across environments was the same whether mixtures or their component lines were grown in pure stand.

The deviation mean squares for multiple pure stands were estimated by multiplying each entry deviation mean square obtained from the joint regression analysis by the number of pure lines used in determining the component mean yield in each replication. A two-tailed F test indicated that a three- and a four-component mixture had deviation mean squares significantly lower than deviation mean squares for multiple pure stands. Regression lines for deviation means squares of mixtures and multiple pure stands have a similar slope (Figure 5). However, the regression line for multiple pure stands (average deviation mean square is 13.09) is consistently higher than the regression lines for mixtures (average deviation mean square is 9.58). The results indicate mixtures have a slight advantage over multiple pure stands for yield stability as measured by deviation mean squares.

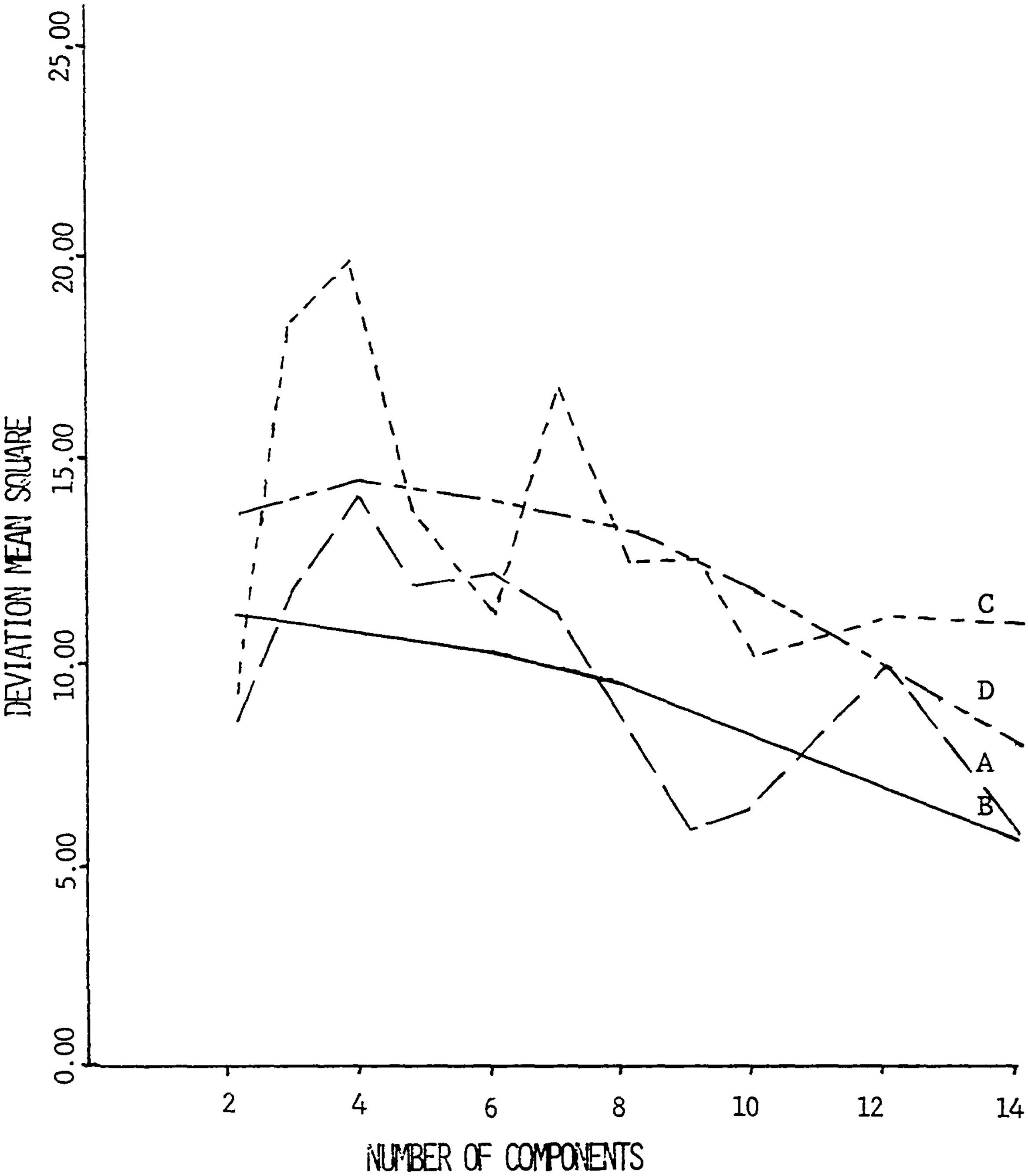

Figure 5. (A) Average deviation mean squares for mixtures with two to 14 components, (B) regression of deviation mean squares for mixtures on number of components ($Y = 11.298 + 0.038X - 0.034X^2$; $R^2 = 0.10$), (C) average deviations for multiple pure stands of the component pure lines, and (D) regression of deviation mean squares for multiple pure stands on number of components ($Y = 13.327 + 0.469X - 0.060X^2$; $R^2 = 0.05$)

DISCUSSION

Heterogeneity and Yield Stability

An objective of this research was to determine the number of cultivars that should be grown by a farmer in pure stand or in a mixture to obtain high yield and stability. A stable entry was defined as having a regression coefficient not significantly different from one and a non-significant deviation mean square. It was not possible from the data to precisely define the number of pure lines needed for stable production due to the variability within each level of heterogeneity for deviation mean squares. Mixtures with two or more components do not necessarily provide greater yield stability than pure lines. Stable production depends on the particular cultivars chosen for either pure stands or mixtures as much as the number involved.

Lack of consistent differences in stability among levels of heterogeneity is common among crop species. Schutz and Brim (1971) tested soybean cultivars that had deviation mean squares similar to two- and three-component mixtures. Rasmusson (1968) found pure lines, two-component, and three-component mixtures of barley that were similar in stability. In maize Eberhart and Russell (1966, 1969) and Weatherspoon (1970) identified single crosses that were as stable as three-way and double-cross hybrids. Falck (1970) tested high yielding maize crosses and found no relationship between stability, as measured by regression coefficient and deviation mean squares, and levels of heterogeneity for five types of crosses. Reich and Atkins (1970) reported that some single-cross sorghum hybrids were as stable as any of the inbred or hybrid mixtures tested. Busch, Hammond, and Frohberg (1976) found little stability advantage for heterogeneous wheat bulks over pure lines as measured by regression coefficients and deviation mean squares.

High yield stability of pure lines is attributable to their individual buffering capacity. The homogeneous soybean lines did not have the populational buffering that the heterogeneous mixtures had, yet many pure lines were as stable as any mixture. Eleven of the 14 lines grown in pure stand had yields not significantly different from the highest yielding line and nine of the 11 lines had nonsignificant deviation mean squares. The ability for individuals within a pure line to be well adapted to a range of environments may have an effect on the average yield across environments. The high yielding soybean lines in this study were selected from the 1974 Northern States Uniform Tests and had been tested over many environments. Soybean lines which have survived extensive yield testing may have a higher yield stability than lines that were not selected for further testing. The relationship between yield performance level and stability of soybean lines in preliminary yield evaluations was studied by Baihaki, Stucker, and Lambert (1976). They found the lower yielding lines which normally would be discarded from advanced testing contributed considerably more to the total genotype x location x year interaction for yield than medium- and high-yielding lines. They concluded that lower yielding lines were the least stable.

Although certain pure lines were as stable as any mixture, there was a general tendency for pure lines to be less stable than mixtures.

The pure lines had the lowest average stability as indicated by average deviation mean squares and the highest percentage of entries with significant deviation mean squares (Figure 4). The relative performance among entries across environments tended to be more consistent for the higher levels of heterogeneity.

Mixtures Compared with Multiple Pure Stands

The use of mixtures to achieve higher yields was not supported by the results, since none of the mixtures had a significantly higher yield than the component mean (Table 10). The mixtures were prepared randomly, without regard to possible intergenotypic interactions, to allow for an unbiased study of stability. Probst (1957) and Hinson and Hanson (1962) tested mixtures prepared without prior knowledge of intergenotypic interactions and found mixtures did not outyield the mean of the components grown in pure stand.

There also were no significant negative yield responses from mixtures which can be considered an advantage when mixtures are used as a hedge against sporadic problems. This suggests that mixtures of resistant and susceptible cultivars can be used without prior yield testing. The estimated yield of the mixture would be the weighted mean of the cultivars in pure stand free of pest and soil problems. The weighted component mean probably would be an underestimate of the yield of the mixture, since most significant deviations in yield from the weighted component mean of high yielding soybean cultivars are positive

(Brim and Schutz, 1968; Fehr and Rodriguez, 1974; Lin and Torrie, 1968; Mumaw and Weber, 1957; Schutz and Brim, 1971).

To determine whether mixtures performed relatively better than their component lines in high- or low-yielding environments, mixture yields and their component means were compared in the three highest- and three lowest-yielding environments. The results showed mixtures had no more yield advantage over their component lines in high- or low-yielding environments than they had across all environments.

In general mixtures provide slightly more stability than can be obtained by growing the component lines in pure stand (Figure 5). The stability advantage of mixtures would be greatest in the presence of sporadic pest and soil problems for which cultivars differ in resistance. Mixtures of high-yielding susceptible and low-yielding resistant cultivars can provide stability without much effect on yield. For example, a 1:1 mixture of Corsoy, a susceptible cultivar, and Amsoy 71, a resistant cultivar, can provide stability in areas of northern Iowa where *Phytophthora megasperma* Drechs. var. *sojae* Hildeb is a problem. The benefit obtained by such a mixture could not be duplicated by growing half of the land area to each cultivar because resistant plants could not compensate for those killed by the disease. Although mixtures have a slight stability advantage over multiple pure stands, mixtures also have several disadvantages. Mixtures do not provide the farmer an opportunity to spread out his harvest which he can do by planting pure stands of different maturing soybean cultivars. Pure seed also can not be saved from mixtures for planting next season. Factors such as pest or soil problems, a longer harvest period, or saving pure seed may be more important than stability in determining whether cultivars should be grown in pure stand or as a mixture.

Yield test data from 25 independent environments from 1969 to 1974 for Amsoy 71, Corsoy, and their 3:1, 1:1, and 1:3 mixtures were analyzed by the joint regression analysis. The estimated yields for components grown in pure stand for each replication also were analyzed. A comparison between the stability of the mixtures and the cultivars grown in pure stand is given in Table 11. All entries had regressions coefficients not significantly different from unity and nonsignificant deviation mean squares. According to the results, a farmer with no soybean pests or soil problems would have equal stability by growing Amsoy 71 and Corsoy in a pure stand or a mixture.

An inconsistency was found for deviation mean squares of Corsoy relative to Amsoy 71 in the 25 independent environments and the 12 environments in this study. In the 12-environment study Corsoy had a highly significant deviation mean square whereas Amsoy 71 had a nonsignificant deviation mean square (Table 13). In the 25-environment study both cultivars had very small deviation mean squares (Table 11). The deviation mean square may be dependent upon the set of environments used and may not be useful in describing the stability of a cultivar in future environments.

Table 11. Comparison of mixtures with the weighted mean of their components for yield, linear regression coefficients, and deviation mean squares for entries prepared from Amsoy 71 and Corsoy

Entry	Yield[a] (q/ha)		Regression coefficient[a]		Deviation mean square[a]	
	Mixture[b]	Pure[c]	Mixture	Pure	Mixture	Pure
Amsoy 71	--	29.5	--	0.95	--	7.41
75% Amsoy 71 25% Corsoy	30.2	29.6	1.07	0.94	2.92	5.43
50% Amsoy 71 50% Corsoy	29.6	29.7	1.08	0.92	5.83	3.61
25% Amsoy 71 75% Corsoy	30.0	29.8	1.0[illegible]	0.91	6.18	6.78
Corsoy	--	29.9	--	0.90	--	6.09

[a]No significant differences within or between columns.

[b]Observed mixture values.

[c]Weighted mean of the components in pure stand.

SUMMARY

Fourteen pure lines and 64 mixtures representing 12 levels of heterogeneity were grown in six locations for two years. A yield stability analysis was conducted to determine how many high-yielding soybean lines should be grown either in pure stand or in a mixture to obtain stable production. A comparison of yield and stability of mixtures was made with the mean yield and stability of the component lines grown in pure stand.

Significant entry x location x year interactions were obtained from the analysis of variance for pure lines, two-, and four-component mixtures, but not for three-component mixtures or those with five to 14 components. A joint regression analysis indicated that none of the regression coefficients of the 80 entries were significnatly different from each other or from zero. Significant deviations from regression mean squares at the 1% probability level were observed for five pure lines, one two-, and one four-component mixture. Average deviation mean squares tended to decrease until mixtures had eight or more components; however, deviation mean squares were more variable among entries within a level of heterogeneity than average deviation mean squares among levels of heterogeneity. It was not possible to precisely define the number of pure lines needed for stable production due to the variability within each level of heterogeneity. Stable production depends on the particular cultivar chosen as much as on the number involved.

There were no significant differences in yield between mixtures and the mean of their components. Mixtures provided slightly more stability as measured by average deviation mean squares than obtained by growing the component lines in pure stand. Other factors such as pest or soil problems, a longer harvest period, or saving pure seed may be more important than stability in determining whether cultivars should be grown in pure stand or as a mixture.

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APPENDIX

Table 12. Composition of equiproportional soybean mixtures

Entry number	Mixture[a] composition	Entry number	Mixture composition
15	7,12	48	5,10,11,17,21,26,27
16	5,13	49	3,6,7,18,20,23,24
17	6,14	50	1,8,9,16,19,22,28
18	2,25	51	1,2,5,6,8,9,10,12
19	11,21	52	2,3,4,7,11,12,13,14
20	17,24	53	1,4,5,6,8,9,10,14
21	4,7,11	54	5,7,11,13,15,18,21,26
22	5,12,14	55	3,16,17,20,22,23,27,28
23	1,3,13	56	6,8,9,12,18,22,25,27
24	1,23,27	57	3,4,5,6,8,10,11,13,14
25	6,8,19	58	1,2,4,7,8,9,12,13,14
26	3,22,25	59	2,4,5,6,7,9,11,13,14
27	7,9,11,13	60	4,8,9,13,14,16,19,20,28
28	1,5,6,8	61	1,3,6,12,17,22,23,25,26
29	2,3,10,12	62	2,5,7,10,11,18,21,24,27
30	19,21,24,27	63	2,3,4,6,7,8,9,11,13,14
31	14,15,17,18	64	1,2,5,6,7,8,12,13,14
32	4,20,22,23	65	2,3,4,5,6,7,8,12,13,14
33	4,5,8,11,13	66	3,7,10,15,17,18,20,22,27,28
34	3,6,10,12,14	67	1,4,6,8,12,13,14,19,21,25
35	1,2,7,9,11	68	2,5,7,9,11,16,23,24,26,27
36	9,12,16,19,23	69	1,2,3,4,5,7,9,10,11,12,13,14
37	4,5,10,17,20	70	1,2,5,6,7,8,9,10,11,12,13,14
38	2,6,7,18,26	71	1,2,3,4,5,6,7,8,9,10,11,13
39	3,4,6,7,8,10	72	4,7,8,9,12,14,15,16,19,20,26,27
40	1,2,5,9,13,14	73	1,3,5,11,13,17,18,21,23,24,25,28
41	4,6,7,8,10,11	74	2,5,6,7,10,11,13,14,17,19,22,23
42	3,11,17,20,25,27	75	1,2,3,4,5,6,7,8,9,10,11,12,13,14
43	13,15,19,21,22,26	76	1,2,3,6,7,8,10,17,21,23,24,25,26,27
44	2,5,18,23,24,28	77	4,5,9,11,12,13,14,15,16,18,19,20,22,28
45	1,2,3,5,12,13,14	78	1,6,8,10,14,19,20,21,22,24,25,26,27,28
46	2,4,9,10,12,13,14	79	2,3,4,5,7,9,11,12,13,15,16,17,18,23
47	1,3,5,6,7,8,11	80	3,7,8,9,10,12,13,14,15,16,17,18,23,28

[a]Numbers refer to pure lines in Table 1.

Table 13. Mean yields, regression coefficients, and deviation mean squares for 80 entries as estimated in the joint regression analysis

Entry number	Yield (q/ha)	Regression coefficient	Deviation mean square
1	26.4	0.89	26.77**
2	26.1	0.87	40.31**
3	27.2	0.96	9.68
4	25.8	0.86	35.87**
5	27.2	0.82	11.19
6	28.5	1.13	12.27
7	29.6	1.08	28.22**
8	27.3	1.02	5.18
9	29.9	1.05	25.24**
10	28.4	1.03	14.73
11	28.0	1.06	13.19
12	29.0	1.15	8.72
13	28.2	0.94	9.87
14	27.8	0.97	4.08
15	29.2	0.98	12.55
16	27.8	0.95	8.76
17	27.8	0.93	2.90
18	28.1	0.93	14.99
19	27.4	1.03	25.69**
20	29.6	1.11	19.58
21	28.1	0.95	7.67
22	28.7	1.05	9.55
23	27.8	1.04	18.20*
24	27.5	1.02	3.95
25	27.3	1.08	9.84
26	29.0	1.03	10.95
27	28.3	1.00	25.01**
28	26.3	0.89	2.14
29	28.0	0.98	14.06
30	27.9	0.95	13.23
31	28.8	0.86	15.98
32	26.8	1.04	13.58
33	26.6	0.98	15.14
34	29.2	1.11	11.77
35	28.0	0.96	8.25
36	29.3	1.04	18.07*
37	28.7	1.03	1.77

*,**Significant at 5% and 1% probability levels, respectively.

Table 13. (Continued)

Entry number	Yield (q/ha)	Regression coefficient	Deviation mean square
38	28.3	0.92	11.93
39	27.3	1.04	11.94
40	28.0	1.05	12.12
41	27.2	1.10	11.98
42	29.6	1.09	10.83
43	28.2	1.06	18.39*
44	28.5	0.97	13.97
45	28.4	1.01	6.24
46	27.8	0.95	15.43
47	26.8	0.92	10.31
48	28.6	1.10	10.34
49	27.3	1.06	11.08
50	27.7	0.87	6.05
51	28.0	1.06	4.04
52	28.3	0.82	14.45
53	28.1	0.98	6.01
54	27.2	0.82	15.93
55	28.3	1.16	11.51
56	27.4	0.84	9.41
57	28.0	0.97	3.79
58	28.1	0.98	6.20
59	28.9	1.04	6.58
60	28.7	1.10	6.29
61	28.7	1.00	10.71
62	29.2	0.92	5.66
63	27.7	1.01	9.59
64	27.9	1.02	3.93
65	27.7	1.15	4.84
66	28.4	1.11	9.12
67	26.7	0.83	15.16
68	29.1	1.06	7.04
69	27.7	0.99	10.80
70	28.2	1.13	4.48
71	28.6	1.03	12.77
72	29.9	1.12	10.92
73	28.4	0.96	3.55

Table 13. (Continued)

Entry number	Yield (q/ha)	Regression coefficient	Deviation mean square
74	27.4	0.92	14.68
75	28.8	1.04	5.42
76	28.3	1.01	16.41*
77	28.2	1.00	6.18
78	28.3	0.91	5.84
79	29.2	1.03	10.77
80	28.7	1.09	9.88

Table 14. Mean squares for the regression of yield, regression coefficients, and deviation mean squares on number of components in 80 entries

Sources of variation	Degrees of freedom	Mean square
	Yield (q/ha)	
Regression	2	1.15
Linear	1	2.02
Quadratic	1	0.29
Lack of fit	77	0.73
	Regression coefficients	
Regression	2	0.0025
Linear	1	0.0049
Quadratic	1	0.0002
Lack of fit	77	0.0074
	Deviation mean squares	
Regression	2	352.56**
Linear	1	574.81**
Quadratic	1	130.29
Lack of fit	77	42.91

**Significant at 1% probability level.

Table 15. Mean squares for the regression of deviation mean squares for mixtures and multiple pure stands on number of components in the entry

Source of variation	Degrees of freedom		Mean square[a]
	Mixtures		
Regression	2		38.16
Linear		1	71.75
Quadratic		1	4.58
Lack of fit	28		25.03
	Multiple pure stands		
Regression	2		34.45
Linear		1	55.05
Quadratic		1	13.85
Lack of fit	28		50.48

[a]No significant mean squares at the 5% probability level.

Table 16. Comparison of observed mixture yields and estimated yields for multiple pure stands in three high- and three low-yielding environments

Entry number	Number of component pure lines	Yield (q/ha) High[a] Mixture[c]	Pure[d]	Low[b] Mixture		Pure
15	2	36.2	38.1	19.0	**	16.2
16	2	36.4	34.5	17.6		18.2
17	2	35.2	36.8	17.3		17.0
21	3	35.0	35.0	17.2		16.3
22	3	36.9	35.6	16.0		17.1
23	3	36.0	35.4	16.6		17.0
27	4	36.0	36.4	17.1		16.8
28	4	33.6	35.7	16.4		16.8
29	4	37.6	36.5	17.3		17.2
33	5	33.2	34.8	16.4		17.0
34	5	39.9	37.3	17.4		16.9
35	5	37.4	35.5	18.5		16.7
39	6	37.6	36.2	16.8		16.8
40	6	36.4	34.7	16.0		17.4
41	6	37.7	36.3	16.4		16.6
45	7	36.0	35.2	17.5		17.2
46	7	36.6	35.8	18.6		17.2
47	7	33.2	35.0	17.0		16.6
51	8	37.8	36.3	16.6		17.0
52	8	34.7	35.5	18.0		16.9
53	8	36.7	35.4	17.1		17.0

[a]High yielding environments, Ames 1975, Kanawha 1975, Sloan 1975, mean yield was 36.2 q/ha, error mean square was 10.02, and coefficient of variation was 8.74%.

[b]Low yielding environments, Farragut 1975, Ottumwa 1975, Spencer 1976, mean yield was 17.07 q/ha, error mean square was 4.43, and coefficient of variation was 12.33%.

[c]Observed mixture yields.

[d]Estimated multiple pure stand yields based on average pure stand yields for lines in a mixture for each replication.

**Mixture and multiple pure stand yields are significantly different from each other at the 1% probability level.

Table 16. (Continued)

Entry number	Number of component pure lines	Yield (q/ha) High[a] Mixture[c]		Pure[d]	Low[b] Mixture	Pure
57	9	36.6		36.1	18.1	17.1
58	9	35.8		35.6	16.9	16.8
59	9	37.3		35.5	18.3	17.4
63	10	36.3		36.4	16.5	16.8
64	10	36.7		36.3	16.2	17.2
65	10	37.7		35.9	15.8	17.1
69	12	35.1		35.7	16.2	17.0
70	12	37.3		36.3	15.5	17.0
71	12	37.6		35.8	17.9	17.0
75	14	38.8	*	35.9	17.2	17.0
Mean		36.4		35.8	17.1	17.0

*Mixture and multiple pure stand yields are significantly different from each other at the 5% probability level.